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Coupling support vector machine and the irrigation water quality index to assess groundwater quality suitability for irrigation practices in the Tana sub-basin, Ethiopia

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ABSTRACT

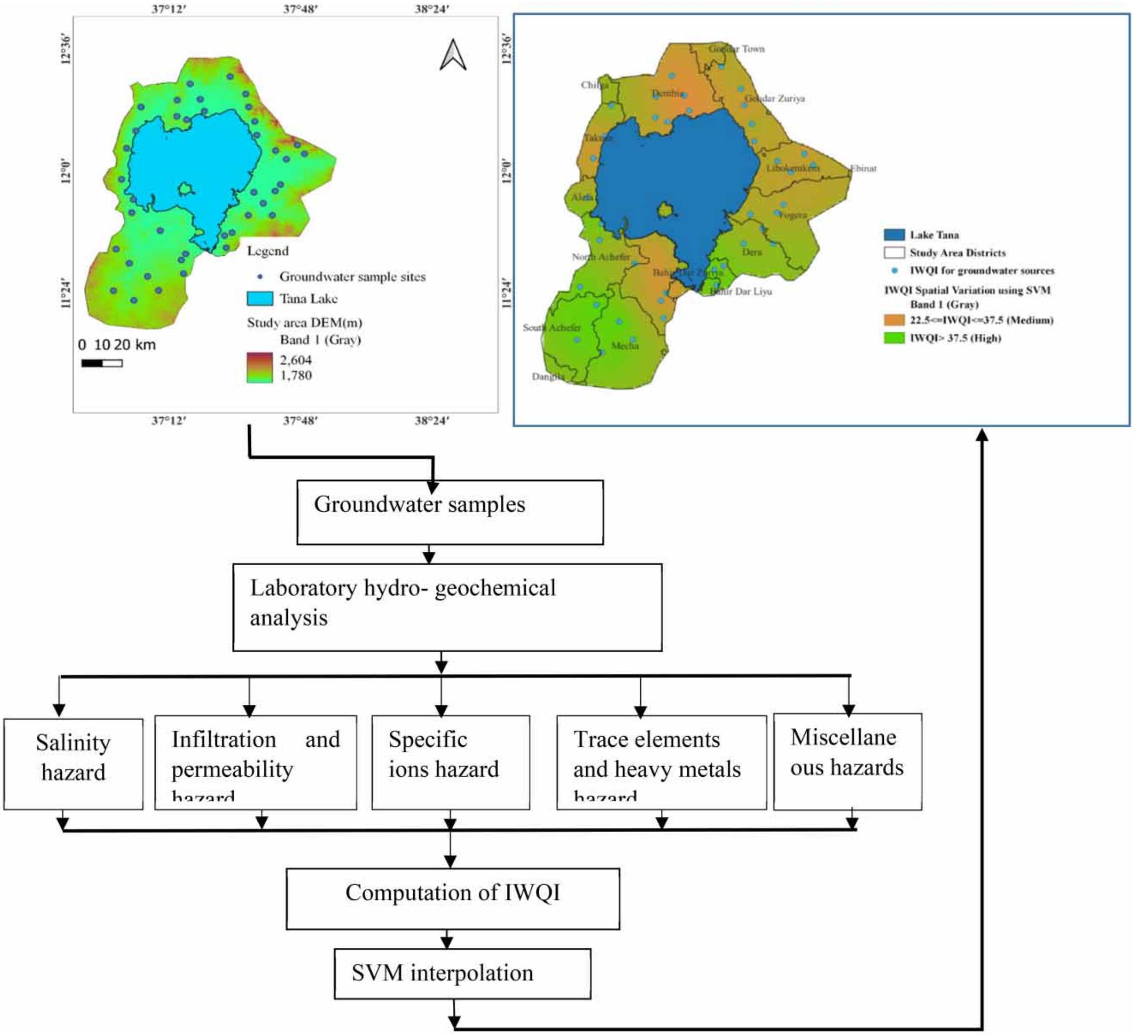
Long-term and sustainable agricultural practices can be achieved through monitoring and evaluation of groundwater quality for irrigation operations. However, less attention was given to irrigation water quality in the Tana sub-basin, Ethiopia. The present study is aimed to assess the seasonal and spatial groundwater suitability for irrigation uses. The groundwater quality parameters measured in 40 samples in each dry and wet season were the pH, electrical conductivity (EC), Na^+, Ca^{2+}, Mg^{2+}, K^+, Fe^{2+}, HCO_3^-, CO_3^{2-}, Cl^-, and NO_3^-. The groundwater suitability for irrigation was assessed using the irrigation water quality index (IWQI) and support vector machine (SVM). The results showed high and medium irrigation suitability classes in the dry and wet seasons. The proportion of groundwater samples in the medium irrigation suitability class in the dry and wet seasons, respectively, was 72.5 and 67.5%. The groundwater in the wet season is comparatively more suitable than that in the dry season, which is attributed to the leaching of accumulated salts during the wet season. To avoid a salinity threat, vigilance should be exercised when using groundwater during the dry seasons. The groundwater quality map developed here for irrigation may aid in locating better-quality groundwater sources for irrigation.

Key words: groundwater quality, irrigation hazards, irrigation suitability, IWQI, SVM

HIGHLIGHTS

- At the headwaters of the Blue Nile, in the Lake Tana sub-basin, a coupled strategy for evaluating groundwater quality for irrigation has been researched during the dry and wet seasons. This study concludes that the rainy season's water quality is superior to the dry, suggesting that using GW in the dry season should be done with prudence.
- The groundwater in the wet season occurs with better quality than that in the dry season since there is water quality improvement due to leaching in the wet season.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Groundwater has paramount importance for domestic, agricultural, and industrial water demands. More than half of the Earth's freshwater has been used across the globe for agricultural uses (Aliyu *et al.* 2017; Aravinthasamy *et al.* 2020). However, groundwater is under stress, creating a serious environmental problem due to anthropogenic activities such as urban expansion, industrialization, and rapid population growth (Xu & Usher 2006; Gupta 2014; Burden *et al.* 2016; Wu & Sun 2016). The presence of contaminants and their vulnerability to aquifers in Ethiopia have been shown in previous studies (UN 1989; Damtie *et al.* 2014; Abiy *et al.* 2016; Akale *et al.* 2017, 2018; Sahele *et al.* 2018). The severity of groundwater pollution has remained a major threat in developing countries, including Ethiopia, due to the lack of implemented governance to protect these precious resources from contaminants (MoWE 2013). The Tana sub-basin was identified as a development corridor by the government of Ethiopia because of its huge and highly interconnected surface and groundwater resources (Tigabu *et al.* 2020).

The region has been endowed with surface water (Lake Tana and four major rivers) and substantial groundwater resources, especially around the Lake Tana flat terrain (Abiy & Melesse 2017; Kindie *et al.* 2019; Berhanu & Hatiye 2020). Tana sub-basin has 1,350 and 3,450 km^2 of land that could be irrigated from groundwater and surface water sources, respectively (Assefa *et al.* 2018). In addition, the irrigation practices reported in the Tana sub-basin (MoWE 2016) revealed that a 128 km^2 area of the sub-basin was irrigated using hand-dug wells. It is also evidenced that small-scale irrigation and household usage are met from groundwater (Mamo *et al.* 2021). These irrigation activities have been carried out in the sub-basin and contribute to agricultural-based economic development, which is now intensively practiced across Ethiopia. For long-term economic development and sustainable productive irrigation practices, the quality of irrigation water should fundamentally be considered at the initial stage to identify the well location, restrict the distribution of groundwater pollutants, and take remedial actions against tainted groundwater sources (British Geological Survey 2001; Bhat *et al.* 2018).

However, groundwater quality and suitability for irrigation purposes have not been given much attention and have yet to be studied in detail across Ethiopia in general and the Tana sub-basin in particular (British Geological Survey 2001; Bhat *et al.* 2018). This research fills the gap and focuses on groundwater quality for irrigation purposes in the study area using the robust interpolation technique support vector machine (SVM) and the irrigation water quality index (IWQI). Analyzing and mapping the water quality controlling parameters using water quality indices are essential for judicious water management practices (Asadi *et al.* 2020).

2. MATERIALS AND METHODS

2.1. Study area description

2.1.1. Location and topography

Tana sub-basin is one of the 16 sub-basins of Abay Basin (Upper Blue Nile Basin) and is located in northwestern Ethiopia. The study covered 7,335 km^2 of the plain area of the Tana sub-basin (Figure 1).

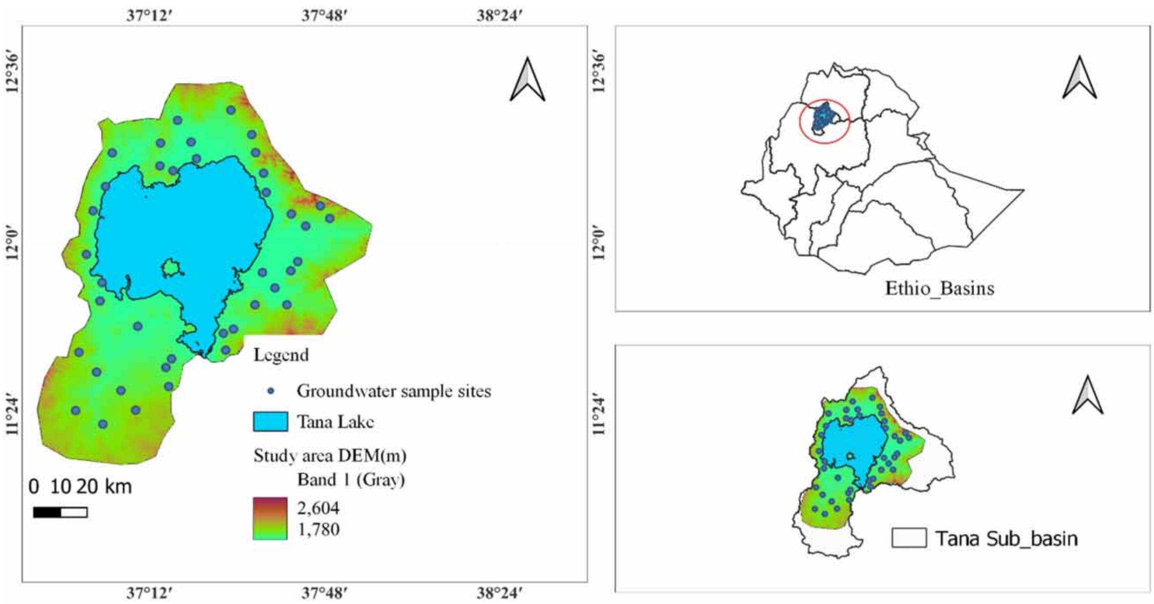


Figure 1 | Study area location map.

2.1.2. Hydrology and climate

Tana sub-basin is a tropical highland with an unimodal wet season ranging from June to September and a dry season from October to March (Duan *et al.* 2018). The seasonal distribution of rainfall is governed by the Inter-Tropical Convergence Zone (ITCZ) (Taye & Willems 2012). The study area has a maximum rainfall ranging from 250 to 330 mm recorded from July to August, and the mean annual rainfall is approximately 1,400 mm (Abebe *et al.* 2017; Kindie *et al.* 2019). The area has also 20 °C as the mean temperature with small seasonal variability (Setegn *et al.* 2010).

2.1.3. Geology

Tana sub-basin has three lithological units, namely, quaternary to recent alluvial-lacustrine sediments, Cenozoic Tarmaber flood basalts, and quaternary scoriacious basalts (GSE 2013; Nigate *et al.* 2017). The dominant lithological unit is Tertiary flood basalts covered with thick alluvial and lacustrine sediments located in the plains of the study area and is the most productive aquifer (Kebede 2012; Nigate *et al.* 2017).

2.1.4. Soil

The dominant soil types of the study area in descending order are haplic luvisols, chromic luvisols, eutric leptosols, eutric vertisols, eutric fluvisols, haplic alisols, and lithic leptosols (SMEC 2008; Kindie *et al.* 2019).

2.1.5. Land Use and Land Cover

The Tana sub-basin land use and land cover (LULC) include agricultural land, grassland, a farm village, forest, shrubland, a town, water, and wetland (ADSWE 2017; Kindie *et al.* 2019; Tigabu *et al.* 2019). Agricultural land is the dominant LULC of the region, which covers more than 60% (Tigabu *et al.* 2019). Most irrigable and extensively irrigated areas have been located at the lowest altitude around Lake Tana (Abera *et al.* 2021). LULC affect hydrological processes such as interception, infiltration, recharge and runoff generation, and groundwater quality.

2.2. IWQI and irrigation hazards

In the present study, QGIS and IWQIs were employed to identify suitable water quality zones for irrigation purposes. This approach is selected because of its popularity in both groundwater and surface water evaluation techniques (Adhikary *et al.* 2012; Venkatramanan *et al.* 2016; Rabeiy 2018; Elubid *et al.* 2019; Baba *et al.* 2020; Mahmud *et al.* 2020). There are numerous traditional irrigation water quality indices to evaluate the suitability of water quality for irrigation purposes. These include EC, sodium absorption ratio (SAR), residual sodium carbonate (RSC), permeability index (PI), Kelly ratio (KR), sodium percentage (Na%), soluble sodium percentage (SSP), magnesium adsorption ratio (MAR), residual sodium bicarbonate (RSBC), and sodium-to-calcium activity ratio (SCAR) (Abdel-Fattah *et al.* 2020; Elsayed *et al.* 2020; Tolera *et al.* 2020). However, the individual traditional indices could not render comprehensive and simplified information to the decision-makers. To overcome this problem, those multiple and fragmented irrigation indices were grouped into five irrigation hazards and used to calculate IWQI in this particular study. These irrigation hazards include salinity, infiltration and permeability problems, specific ion toxicity, trace elements and heavy metals toxicity, and miscellaneous hazards (Narany *et al.* 2016; Asadi *et al.* 2020). The salinity hazard is measured by using the EC or TDS, while the infiltration and permeability hazards are evaluated using SAR. The specific ions toxicity hazards are diagnosed using ions such as chloride and RSC whereas the trace elements and heavy metals toxicity hazards are being evaluated using the levels of iron (Fe^{2+}) and other elements in irrigation water (Ayers & Westcott 1994; Asadi *et al.* 2020). Finally, the miscellaneous hazards of irrigation water are evaluated using parameters such as pH, nitrate, and bicarbonate (Ayers & Westcott 1994; Simsek & Gunduz 2007; Narany *et al.* 2016; Asadi *et al.* 2020).

To measure the sodium contents and their hazard to crops, indices such as SAR, Na%, PI, KR, SSP, RSBC, and SCAR can be applied. However, the most basic parameters among the aforementioned indices are SAR, Na%, and PI (Chidambaram *et al.* 2022).

In the present study, EC for the salinity hazard, SAR, PI, and Na% for infiltration and permeability hazards; chloride and RSC for specific ions toxicity hazards; iron for trace elements and heavy metals toxicity hazards; and pH, nitrate, and bicarbonate for miscellaneous hazards were considered according to the availability of the data. The equations of the indices such as SAR, PI, Na %, and RSC employed are given in Equations (1)–(4), respectively.

$$\mathrm{SAR} = \frac{[\mathrm{Na}^{+}]}{\sqrt{([\mathrm{Ca}^{2+}] + [\mathrm{Mg}^{2+}])/2}} \tag{1}$$

$$\mathrm{Na\%} = \frac{\mathrm{Na}^{+} + \mathrm{K}^{+}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+}\ \mathrm{K}^{+}} \times 100 \tag{2}$$

$$\mathrm{PI} = \left(\frac{\mathrm{Na}^{+} + \sqrt{\mathrm{HCO}_3^{-}}}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^{+}}\right) \times 100 \tag{3}$$

$$\mathrm{RSC} = (\mathrm{CO}_3^{2-} + \mathrm{HCO}_3^{-}) - (\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}) \tag{4}$$

All ion concentrations in Equations (1)–(4) are in milliequivalent per liter (meq/L) or millimole per liter (mmol/L).

The weights (from 1 to 5) and ratings (from 1 to 3) were given to these five irrigation hazards based on their significant effect on irrigation water (Ayers & Westcott 1994; Simsek & Gunduz 2007; Narany *et al.* 2016). The most important irrigation hazard (salinity hazard) was given the highest weight value of 5 whereas the least important (miscellaneous hazard) was provided with the lowest weight value of 1 as tabulated in Table 1. The rates were also given to each irrigation water quality parameter's ranges, as depicted in Table 1.

Table 1 | Irrigation water suitability modified from Ayers & Westcott (1994); Chidambaram *et al.* (2022); Narany *et al.* (2016); Simsek & Gunduz (2007)

Irrigation hazard	Irrigation water quality parameter	Weight (w)	Range	Rating (Ri)	Irrigation suitability
Salinity	EC(μS/cm cm)	5	$EC < 700$	3	High
			$700 \leq EC \leq 3,000$	2	Medium
			$EC > 3,000$	1	Low
Infiltration and permeability	SAR	4	$SAR < 3$	3	High
			$3 \leq SAR \leq 9$	2	Medium
			$SAR > 9$	1	Low
	Na%	4	$Na\% < 25$	3	High
			$25 \leq Na\% \leq 50$	2	Medium
			$Na\% > 50$	1	Low
	PI	4	$PI < 40$	3	High
			$40 \leq PI \leq 60$	2	Medium
			$PI > 60$	1	Low
Specific ions	Na (RSC in mmol/L)	3	$RSC < 1.25$	3	High
			$1.25 \leq RSC \leq 2.5$	2	Medium
			$RSC > 2.5$	1	Low
	Cl (mg/L)	3	$C\,l < 140$	3	High
			$140 \leq Cl \leq 350$	2	Medium
			$Cl > 350$	1	Low
Trace and heavy metals	Fe (mg/L)	2	$Fe < 0.1$	3	High
			$0.1 \leq Fe \leq 1.5$	2	Medium
			$Fe > 1.5$	1	Low
Miscellaneous	NO_3^- (mg/L)	1	$NO_3^- < 5$	3	High
			$5 \leq NO_3^- \leq 30$	2	Medium
			$NO_3^- > 30$	1	Low
	HCO_3^- (mg/L)	1	$HCO_3^- < 90$	3	High
			$90 \leq HCO_3^- \leq 500$	2	Medium
			$HCO_3^- > 500$	1	Low
	pH	1	$7 < pH < 8$	3	High
			$6.5 \leq pH \leq 7$ or $8 \leq pH \leq 8.5$	2	Medium
			$pH < 6.5$ or $pH > 8.5$	1	Low

Finally, these irrigation hazards were used to compute the IWQI and to evaluate whether the groundwater quality of the study area is suitable for irrigation or not. The suggested IWQI, which assesses the joint effect of irrigation hazards, could be calculated using Equations (5) and (6) (Asadi *et al.* 2020).

$$Wi = \frac{w_i}{N}\sum_{i=1}^{N} R_i \tag{5}$$

where W_i is the contribution of each one of the irrigation hazards; w_i is the weight of each irrigation water quality parameter; N is the total number of parameters and R_i is the rating value of each parameter's class.

$$\mathrm{IWQI} = \sum_{i=1}^{N} Wi \tag{6}$$

2.3. Geospatial analysis

Various common geospatial tools are available to interpolate geospatial variables in GIS environments, such as inverse distance weighting (IDW) and different types of kriging. In recent years, however, machine-learning interpolation techniques have become more efficient than the earlier and standard interpolation techniques (Kim *et al.* 2022; Pereira *et al.* 2022). SVM is one of the machine-learning algorithms that performs superior to an artificial neural network (Kim *et al.* 2022). Pereira *et al.* (2022) also selected SVM to develop the Smart-Map QGIS plugin for interpolation due to its ability to perform IDW, ordinary kriging, and handle smaller to larger size datasets. Because the Smart-Map QGIS plugin is easy and powerful for interpolation, it was used in this study.

2.4. Groundwater sampling

Sample collection was carried out in 2022 during the dry (January–April) and wet (June–September) seasons using the purposive sampling method. The factors considered during sample site selection were land use/cover, soil cover, geology, accessibility, and the availability of groundwater sources.

Multi-meter 800 Palintest portable device was used to measure pH and EC at the site. Polypropylene (0.5 L in size) bottles appropriately rinsed with distilled water were used to collect 40 groundwater samples (Figure 1 and Table 2) in each dry and wet season.

Table 2 | Groundwater samples and location names

S. No.	**Location name**	**Sample name**	***X*-coordinate**	***Y*-coordinate**	***Z* (Elevation)**
1	Zenzelima	ZSHD	332248	1285566	1918
2	Robit Town	ROBTHD	331410	1292098	1856
3	Gombat	GMBSHD	335177	1293707	1889
4	Birra	BIRHD	371369	1336355	1930
5	Wusha Tirs	LKWTHD	357016	1338127	1911
6	Wonzma	WONZDW	355195	1303045	1828
7	Burha	BURHD	362339	1333456	1814
8	Woreta	WTACMW	356706	1316174	1809
9	Hamusit	HTCHW	343287	1303103	1941
10	Woreta Town	WTDW	359331	1319728	1813
11	Jigina K/Mihret	JKMHD	350738	1309567	1798
12	Wotet Abay	WAHW	286154	1257223	1934
13	Merawi Town	MTSW	298446	1262577	1993
14	Ahuri Keltafa	AKHW	276013	1262571	2065
15	Chanita sostu	CHSHD	309848	1279023	1864
16	Maezent	LOMSW	312016	1282354	1837
17	Amarit Town	AMTSW	293019	1270191	1896
18	Yiloma	YILHD	310863	1271636	1920
19	Lihudi	LHTHD	283945	1277408	1890
20	Ambeshen	AMBHW	277402	1285115	2036
21	Forhe	FORHW	285416	1304911	1924
22	Chimba	CHIMMW	299447	1295007	1810
23	Amberger	AMBHSW	280471	1322987	1860
24	Kunzila	KUNMW	286232	1312039	1803
25	Chewdiba	CHEWMW	290400	1362205	1885
26	Delhi	DELHD	287773	1349209	1787
27	Bergen	BERHD	283080	1339817	1838
28	Teda	TEDMW	334723	1378422	1902
29	Gomengie	GOMHD	343828	1361949	1895
30	Abrjiha	ABRJHD	308139	1357013	1855
31	Maksegnit	MAKMW	342430	1368910	1912
32	Serwuha	SERWMW	314819	1374611	1828
33	Chuhit	CHUAHD	308409	1365845	1893
34	Guramba	GURHD	319784	1366172	1794

(*Continued.*)

Table 2 | Continued

S. No.	Location name	Sample name	*X*-coordinate	*Y*-coordinate	*Z* (Elevation)
35	Gorgora	GORTDW	312999	1355114	1798
36	Achirra	ACHHD	321769	1359740	1784
37	Addis Zemen	ADDZDW	367851	1341211	1961
38	GiGi	GIGIHD	346745	1353986	1866
39	Mitra	MITHD	347702	1346538	1803
40	Hodgebeya	HODGHD	346115	1315565	1785

A portable refrigerator device (KaVIR TERMOOS) was used to transport the collected groundwater samples to Abbay Basin Authority (ABA) laboratory center, the Organization for Rehabilitation and Development (ORDA), and the Amhara Design and Supervision Works Enterprise (ADSWE). The samples were then analyzed for nine hydro-geochemical parameters, including Ca^{2+}, Na^{+}, K^{+}, Mg^{2+}, Fe^{2+}, Cl^{-}, HCO_3^{-}, CO_3^{2-}, and NO_3^{-}. The Atomic Absorption Spectroscopy (AAS) method measured sodium ions and the remaining parameters were measured using the Palintest 800 method. The general recapitulated flow chart is depicted in Figure 2.

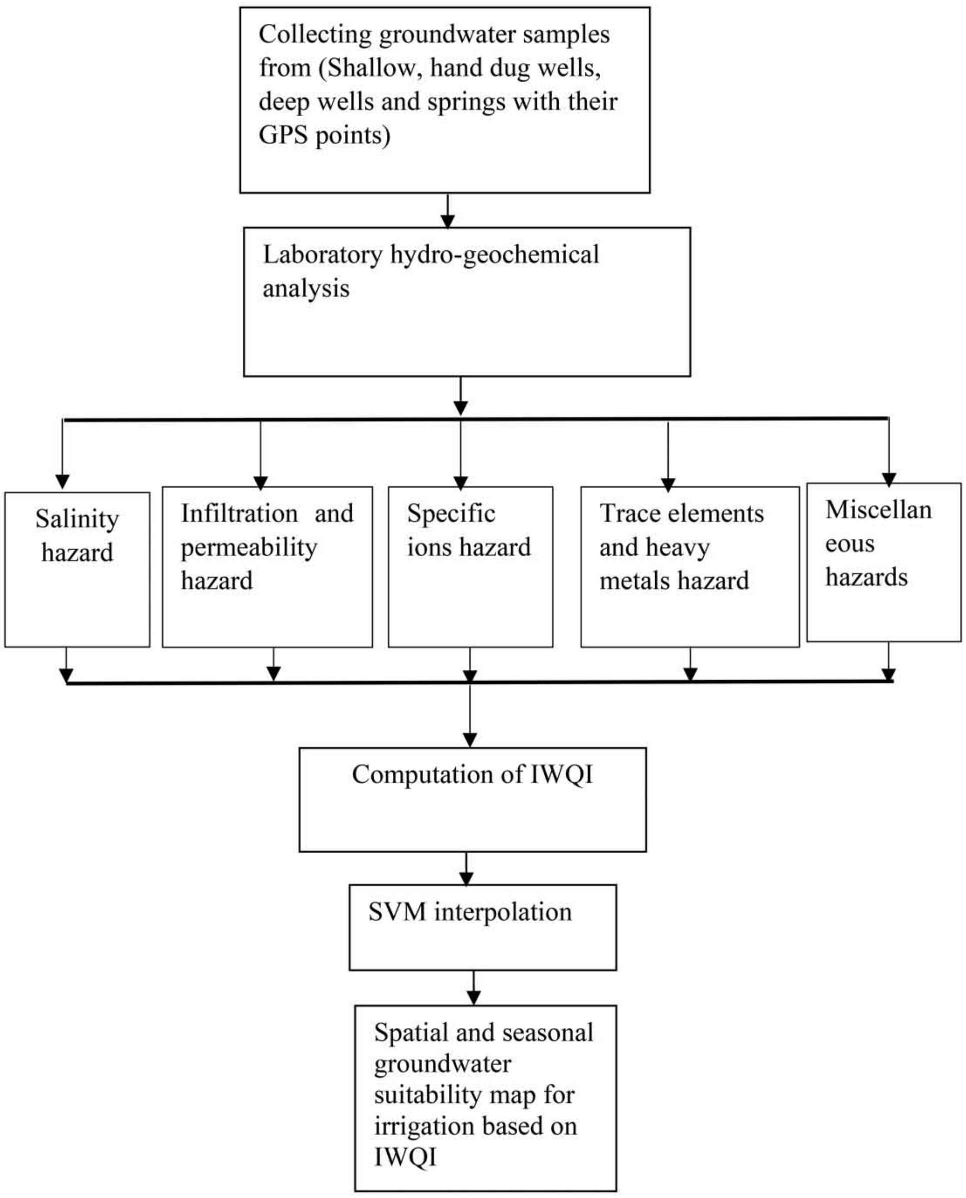


Figure 2 | General flow chart for developing spatial and seasonal groundwater quality map for irrigation use.

3. RESULTS AND DISCUSSIONS

3.1. Hydro-geochemical parameters

The hydro-geochemical parameters employed in five different water quality parameters were pH, EC, Ca^{2+}, Na^{+}, K^{+}, Mg^{2+}, Fe^{2+}, Cl^{-}, HCO$_3^-$, CO$_3^{2-}$, and NO$_3^-$. The major influencing water quality parameters determining the irrigation suitability variation in the two study seasons were EC (Table 1). The radial diagram (Figures 3 and 4) shows that the dominant cations in decreasing order were Na^{+}, Ca^{2+}, Mg^{2}, and dissolved ferrous (Fe^{2+}) in both the dry and wet seasons. On the other hand, the dominant anions in descending order were HCO$_3^-$, CO$_3^{2-}$, Cl^{-}, and NO$_3^-$ in the dry and HCO$_3^-$, CO$_3^{2-}$, NO$_3^-$, and Cl^{-} in the wet seasons. The concentrations of the measured parameters were observed to be greater in the wet season than in the dry season. A semi-logarithmic Schoeller plot in mg/L also revealed the seasonal variations and actual concentrations of Na^{+}, Ca^{2+}, Mg^{2}, HCO$_3^-$, Cl^{-}, and NO$_3^-$ anions, as depicted in Figures 5 and 6.

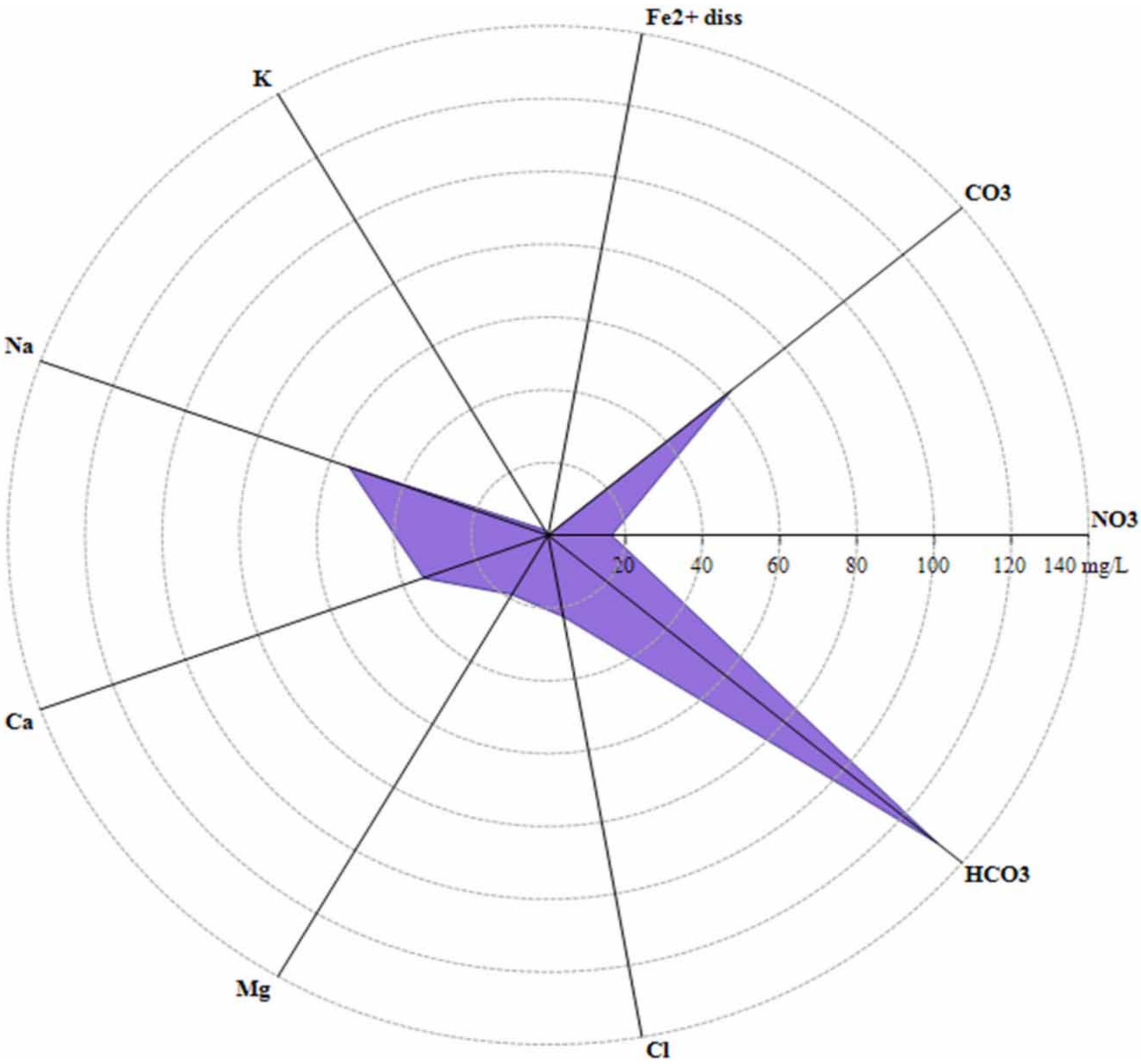


Figure 3 | Dry season groundwater samples radial diagram showing average concentrations of parameters in mg/L.

3.2. Irrigation hazards

In the evaluation of irrigation water quality, five irrigation hazards, including salinity hazard, infiltration and permeability, specific ions, trace and heavy metals, and miscellaneous hazards were considered in the present study and provided in the following sections.

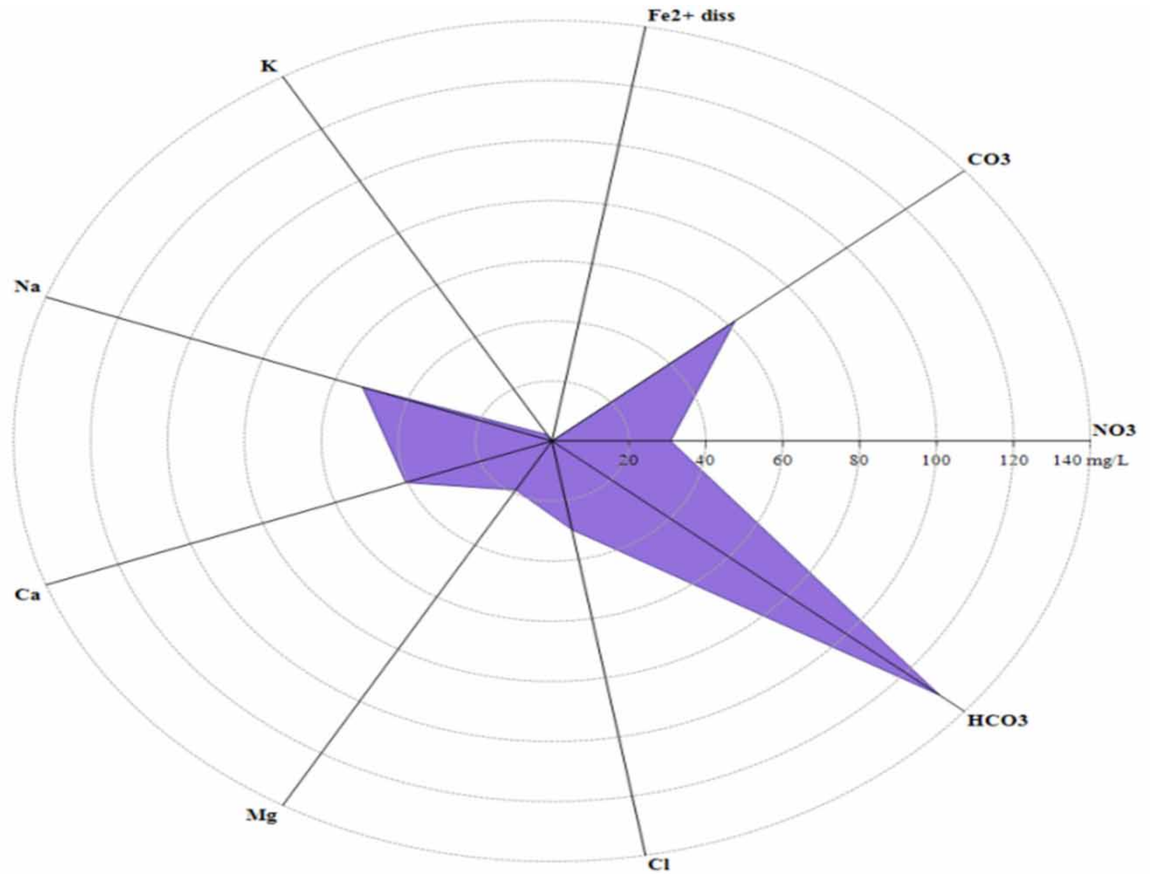


Figure 4 | Wet season groundwater samples radial diagram showing average concentrations of parameters in mg/L.

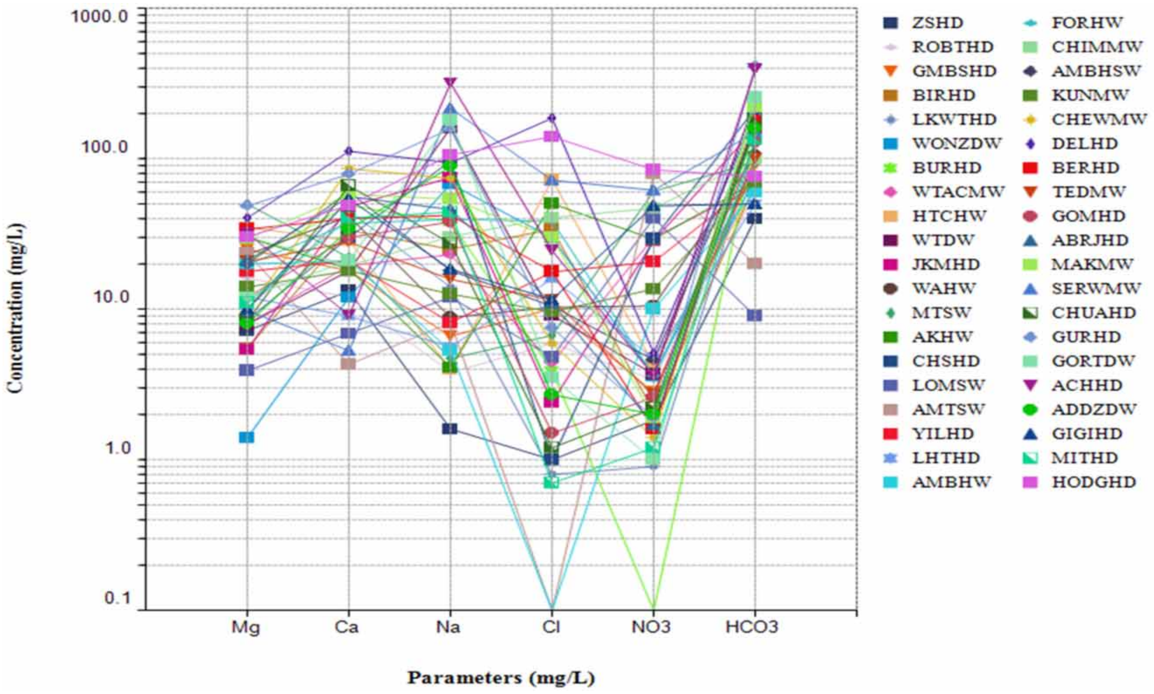


Figure 5 | Schoeller diagram for dry season groundwater samples listed in the legend (right) showing actual concentrations of major cations and anions.

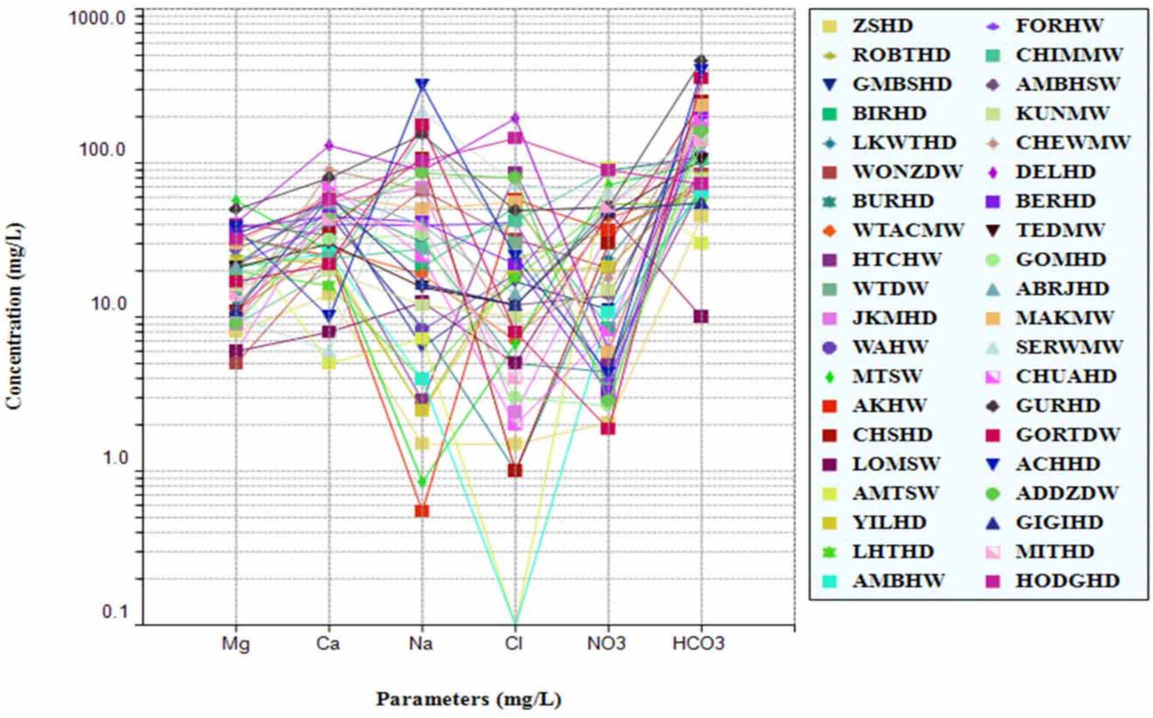


Figure 6 | Schoeller diagram for wet season groundwater samples listed in the legend (right) showing actual concentrations of major cations and anions.

3.2.1. Salinity hazard

Salinity hazard assessment is very important in irrigation water quality. It was measured using electrical conductivity (EC). It depends on the amount of salt content dissolved in irrigation water. Salinity hazards or high salt accumulation in the crop root zone reduce the amount of water available to the crop roots, which may adversely affect the crop and lead to physiological drought. The salts in groundwater intended to irrigate crops could be sourced from naturally dissolved minerals, weathered rocks, and anthropogenic effects such as domestic and industrial discharges (Simsek & Gunduz 2007). This problem could also be aggravated when irrigated soil has a significant salt content. In the study area's irrigable land, there is mostly slightly saline soil in the upper part (BoEPLAU 2015). Therefore, high-quality irrigation water usually has an EC value of less than 700 μS/cm (Simsek & Gunduz 2007; Asadi *et al.* 2020). The classification of irrigation water based on EC is given in Table 1. The salinity hazard (C) was assessed in combination with the sodium hazard (S) in terms of SAR. The Wilcox diagram was applied to cluster the groundwater quality based on these hazards (Figures 7 and 8). In both the dry and wet season groundwater samples, the combination of C and S resulted in five zones: C1–S1, C2–S1, C3–S1, C3–S2, and C3–S3. In the dry and wet season groundwater samples, the C1–S1 zone covered only 2.5 and 5% of the groundwater samples, respectively. On the other hand, the dominant irrigation water zone was C3–S1, which consisted of 65 and 60% of the groundwater samples in the dry and wet seasons, respectively. The C2–S1 zone covered 20 and 27.5% in the dry and wet seasons, respectively, whereas the C3–S2 and C3–S3 only had 5% each in both the study seasons.

Regarding the suitability of the water zones, C1–S1 is suitable for all soil types and crops, and C2–S1 zone could be used to irrigate all types of soils with a modest leaching technique (Subba Rao 2018; Aravinthasamy *et al.* 2020). The C3–S1 zone groundwater samples may be used in areas with appropriate drainage facilities and for salt-tolerant crops, whereas the remaining C3–S2 and C3–S3 zones could be applied in a very good permeable soils and for salt-tolerant crops (Aravinthasamy *et al.* 2020). The availability of salinity and sodicity in the present study area was really matched to the previous study conducted by Daba & Qureshi (2021).

3.2.2. Infiltration and permeability hazards

Infiltration and permeability of croplands depend on the quality of irrigation water, the soil structure, the soil composition, and the soil organic content. The permeability and infiltration hazards mainly occur when high sodium ions lower the time irrigation water enters the bottom layer of soils through infiltration. This problem

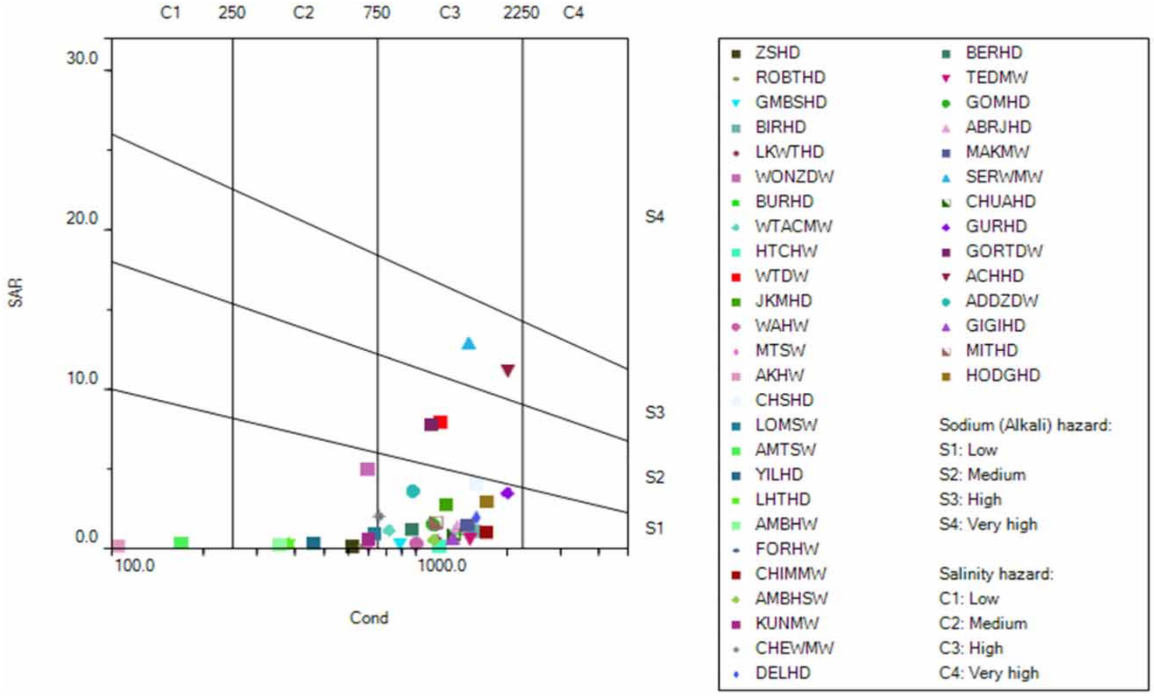


Figure 7 | Wilcox diagram of dry season groundwater samples.

hampers the crop roots from extracting the desired amount of irrigation water, which in turn results in reduced agricultural products. To measure the sodium contents and their hazard to crops, different indices such as SAR, Na%, PI, KR, SSP, RSBC, and SCAR could be applied. However, the most basic parameters among the aforementioned indices are Na%, PI, and SAR (Chidambaram *et al.* 2022). Therefore, the SAR, the Na%, and the PI were selected to determine the infiltration and permeability hazards in this particular study.

The SAR values of the groundwater in the study area ranged from 0.09 to 12.80 (average = 2.11) in the dry season and 0.02–12.42 with a 1.86 average value in the wet season. The dry season groundwater samples had more salinity than the wet season, which may mainly be attributed to rainfall during the wet season diluting the groundwater salinity (Lu *et al.* 2015). According to Table 1, 80, 15, and 5% of both the dry and wet

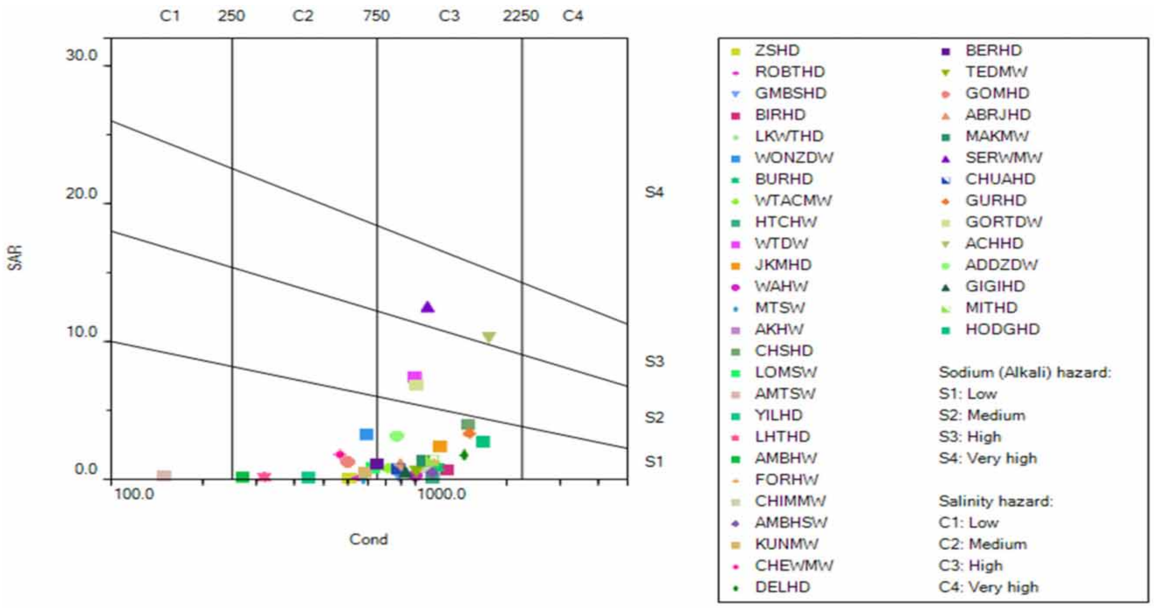


Figure 8 | Wilcox diagram of dry season groundwater samples.

season groundwater samples were classified as high ($SAR < 3$), medium ($3 \leq SAR \leq 9$) and low ($SAR > 9$) irrigation water quality, respectively. The samples SERWMW and ACHHD, which covered 5%, had SAR values greater than 9 due to high sodium ion content. The sodium percentage (Na%) values ranged from 3.75 to 89.76 (average = 33.96) in the dry season and 0.60–89.26 (average = 29.68) in the wet season. The Na% values are more reduced in the wet season than the dry season, which may be related to Na ion decline in the wet season due to the leaching of Na ion with precipitation in the wet season (Lu *et al.* 2015).

As per Table 1, the high irrigation water quality is less than 25 Na% value. However, only 42.5 and 50% of the groundwater samples were within this class in the dry and wet study seasons, respectively. The remaining 37.5 and 20% of the dry season and 32.5 and 17.5% of the groundwater samples were classified as medium ($25 \leq Na\% \leq 50$) and low ($Na\% > 50$) irrigation water quality, respectively. The PI values stretched from the lower 26.44 value to the higher 110.43 value with an average of 62.24 in the dry season. On the other hand, the PI values in the wet season ranged from 21.30 to 104.27 with an average value of 55.76. The higher values of PI observed during the dry season may be attributed to the higher values recorded in this study season. The high irrigation water quality is limited to a 40 PI value, as envisaged in Table 1. However, only 15 and 25% of the groundwater samples fall in high-quality irrigation water in the dry and wet seasons, respectively. On the other hand, 45 and 35% of the groundwater samples were above 60 (low) for irrigation water quality.

3.2.3. The specific ions toxicity hazards

Ions such as chloride, sodium, and boron could pose toxicity problems for crops if they are present in higher concentrations in irrigation water or agricultural land. The degree of toxicity of these specific ions differs based on plant types and the root water uptake rate of crops. For example, perennial-type crops are more sensitive to this type of toxicity hazard than that of annual crops.

Chloride ion is usually available in irrigation waters. In limited concentrations, it is vital for crops. However, the higher concentration of chloride could pose toxicity to sensitive plants and result in leaf tissue disease (Simsek & Gunduz 2007). In general, irrigation water with chloride values below 140 mg/L is considered highly suitable for irrigation (Table 1). The chloride ion value ranged from 0.00 to 186.00 mg/L (mean = 22.68 mg/L) and 0.00 to 195.00 mg/L (mean = 29.98 mg/L) in the dry and wet seasons, respectively. Fortunately, 95% of the groundwater samples were in the domain of high irrigation in both seasons. The remaining two groundwater samples (DELHD and HODGHD) covering 5% were falling in the medium ($140 \leq Cl \leq 350$ mg/L) irrigation suitability range (Table 1).

The toxicity of sodium can be manifested on plants as leaf burn, scorch, and dead tissue along the outside edges of leaves (Simsek & Gunduz 2007). As previously mentioned, high accumulations of sodium also pose infiltration and permeability hazards. In this irrigation hazard, a sodium ion effect was measured using RSC (Equation (4)). The presence of carbonates (carbonate and bicarbonate) in excess of irrigation water renders the chance of sodium ion to be dominant since the carbonates could form precipitates with calcium and magnesium ions (Nagaraju *et al.* 2014). The result of RSC values varied from −4.6 to 6.40 mmol/L (mean = 1.77 mmol/L) in the dry and −4.42 to 8.43 mmol/L (mean = 2.36 mmol/L) in the wet season. The RSC values revealed that only 12.5% of the groundwater samples in both seasons had no residual carbonate due to negative values, whereas the remaining 87.5% had positive values, indicating the availability of residual carbonate, which may negatively affect crop production. The value of RSC in the high irrigation suitability class is less than 1.25 mmol/L (Table 1). However, only 35 and 20% of the groundwater samples fall in this class in the dry and wet seasons, respectively. The groundwater samples under the low ($RSC > 25$) class (Table 1) also covered 27.5 and 47.5% in the dry and wet seasons, respectively.

3.2.4. The trace elements and heavy metal toxicity hazards

Trace elements and heavy metals are toxic if plant roots take them up in excess amounts compared to what the crops require. They negatively affect the plant's growth, yield, and health. In the present study, only ferrous (Fe^{2+}) concentration measurement was carried out to identify the presence of trace and heavy metal hazards. The ferrous ion concentration varied from 0.00 to 0.35 mg/L (average = 0.03 mg/L) and 0.00 to 0.54 mg/L (average = 0.04 mg/L) in the dry and wet seasons, respectively. The high irrigation suitability class has values greater than 0.1 mg/L (Table 1). The groundwater samples covering 87.5% fit this category and thus, were highly suitable for irrigation. The other 12.5% of the groundwater samples were medium irrigation water quality.

3.2.5. Miscellaneous hazards

Miscellaneous crop hazards may arise due to the presence of additional irrigation water parameters, which must be studied to assess the suitability of water for irrigation purposes. These parameters include pH, bicarbonate, and nitrate. The pH value influences soil quality and plant growth by governing the carbonate equilibrium, heavy metal content, and the relative ratio of nitrogen components (Simsek & Gunduz 2007). In acidic waters, vital elements such as calcium, aluminum, and magnesium are not appropriately absorbed by plants, but not in essential waters. On the other hand, alkaline irrigation waters could increase the calcium carbonate accumulation and the sodium ion concentrations in the soil, which may lead to sodium hazards (Simsek & Gunduz 2007). The suitable range of pH values for irrigation waters is between 7 and 8, as tabulated in Table 1. The analysis revealed that pH values ranged from 6.00 to 7.80, with a 6.88 mean in the dry season and 6.07 to 7.94, with an average of 7.05 in the dry and wet seasons, respectively. The groundwater samples covering 45 and 62.5% fit the high irrigation suitability class in the dry and wet seasons, respectively. The low irrigation suitability ($\mathrm{pH} < 6.5$ or $\mathrm{pH} > 8.5$) covered 22.5% in the dry and 20% in the wet study season.

High levels of bicarbonate render the chance for sodium ions to be dominant in irrigation groundwater (Nagaraju *et al.* 2014). The bicarbonate concentration values below 90 mg/L are considered ideal for irrigation purposes (Table 1). The values of the bicarbonate ion concentration in mg/L stretched from 9.00 to 410.00 with an average of 131.43 from 10.00 to 460.00 with a mean of 146.45 in the dry and wet seasons, respectively. The nitrate ion concentrations were significant in the wet and dry seasons. However, in the two study seasons, only 37.5% of the groundwater samples were highly suitable for irrigation, and the remaining 62.5% were under medium suitability.

The source of nitrogen is the required amount of nitrate used as fertilizer for crops. However, excessive amounts above the required levels could cause untimely growth or unsightly deposits on fruits, delayed crop maturity, and yield reduction (Simsek & Gunduz 2007; Ahmed *et al.* 2020). Fortunately, such problems accompanied by nitrate hazards could be tackled by properly applying fertilizers and excellent irrigation management (Shaviv & Mikkelsen 1993; Simsek & Gunduz 2007; Ahmed *et al.* 2020). The ideal nitrate values for irrigation waters should be below 5 mg/L (Table 1). The results of nitrate concentration in mg/L varied from 0.00 to 84.50 with a 16.46 mean value in the dry season and 1.88 to 94.00 with an average value of 30.82 in the wet season. Only 60 and 25% of the groundwater samples had nitrate values less than 5 mg/L, which were highly suitable for irrigation in the dry and wet seasons, respectively. On the other hand, 17.5 and 42.5% of the groundwater samples were under low irrigation water quality. The reduced quality during the wet season may be attributed to the application of many fertilizers and manures, leachate from the deposited domestic and animal wastes due to the precipitation and flooding in the wet season.

3.3. Spatial and seasonal variation of groundwater quality based on the IWQI

The seasonal and spatial groundwater quality suitability analysis for irrigation uses was carried out by computing the IWQI with Equation (6) and the SVM interpolation method. The IWQI calculation gave three different IWQI values (i.e. 15, 30, and 45) according to the corresponding parameters' rating factors tabulated in Table 1. The medians of these three IWQI values were used to determine the lower and upper limits (Table 3) used in each class of groundwater quality suitability for irrigation (Simsek & Gunduz 2007; Asadi *et al.* 2020).

Table 3 | IWQI and irrigation suitability classes

IWQI ranges	Irrigation suitability class
$\mathrm{IWQI} < 22.5$	Low
$22.5 \leq \mathrm{IWQI} \leq 37.5$	Medium
$\mathrm{IWQI} > 37.5$	High

The IWQI values ranged from 29.3 to 44.3 with an average value of 35.8 and from 27.7 to 44.3 with an average value of 35.7 in the dry and wet seasons, respectively. It seemed that IWQI values were somehow reduced in the wet season. The medium irrigation suitability class covered 72.5 and 67.5% of the groundwater samples in the dry and wet seasons, respectively. This percentage difference implied that groundwater quality suitability for irrigation is somehow more available in the wet season than in the dry season, which may be attributed to the presence of salinity leaching by rainfall in the wet season (Lu *et al.* 2015). In both the study seasons, the irrigation suitability classes were medium and high.

Since the irrigation activities are carried out in the dry season, only this season's groundwater quality suitability map for irrigation was produced using the SVM interpolation method. As shown by the red hue in Figure 9, the majority of the study area's medium irrigation suitability class was located in the northern section and less in the southern part. The medium irrigation suitability class of the study area (part of the Bahir Dar Zuria district) is localized where it was identified, in the previous study, as vulnerable to high pollution risk area (Abiy *et al.* 2016).

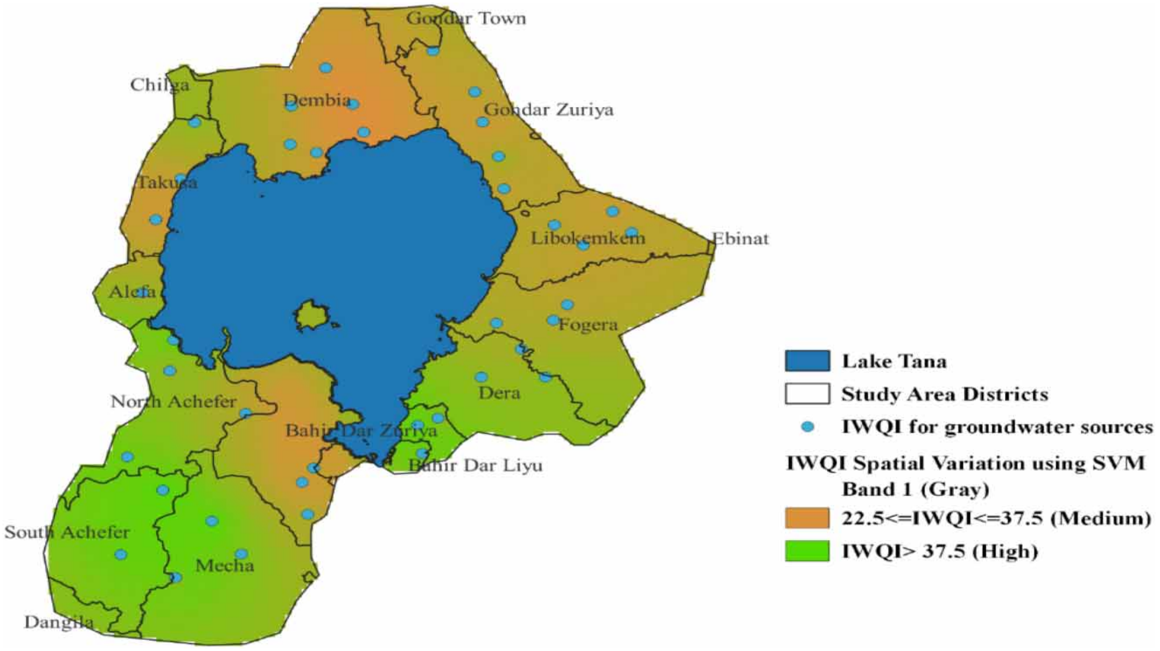


Figure 9 | Spatial variation of groundwater samples based on the IWQI. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wpt.2023.055.

4. CONCLUSION

Groundwater quality suitability for irrigation use was assessed by the IWQI and the powerful interpolation tool, SVM. The groundwater quality parameters considered in the present study were pH, EC, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Fe^{2+}, Cl^{-}, HCO_3^{-}, CO_3^{2-}, and NO_3. Most of these parameters, except EC and Na^{+}, have greater concentrations in the wet season than in the dry season.

Groundwater quality suitability evaluation for irrigation purposes using the IWQI is the utmost in combining many irrigation hazards and indices to provide straightforwardly understandable information to the stakeholders. Salinity hazards, infiltration and permeability hazards, specific ion hazards, trace and heavy metal hazards, and miscellaneous hazards were considered to compute the IWQI. The results of the IWQI revealed that the irrigation suitability of the groundwater samples was high to medium. The high suitability class covered 27.5 and 32.5% of the groundwater samples in the dry and wet seasons, respectively, implying decreased irrigation suitability due to more accumulated salinity in the dry season than in the wet season. The produced groundwater suitability map for irrigation is a prominent provision to the concerned bodies to help indicate where high and medium groundwater sources are in the study region. In the study area, irrigation activities using groundwater sources are carried out in the dry season. However, the majority of the medium irrigation suitability class was observed in this season, mainly due to the salinity effect. This should alarm the concerned bodies to mitigate, manage, and control groundwater resources from salinity and other mentioned hazards in this study.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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